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DEVELOPMENT OF DISCRIMINATION, DETECTION, AND LOCATION CAPABILITIES IN CENTRAL AND SOUTHERN ASIA USING MIDDLE-PERIOD SURFACE WAVES RECORDED BY A REGIONAL ARRAY

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13. ABSTRACT *(Maximum 200 words)*
This research is dedicated to the investigation of the relevance and use of intermediate period (5 - 25 s) surface wave data in problems of detection, discrimination, and the accurate location of small events using regional array data. It is focused on analysis of data from earthquakes throughout Central and Southern Asia and the Middle East and nuclear explosions at Lop Nor within 15 - 25 degrees of the Kyrghiz Telemetered Seismic Network. The main efforts during the 6.5-month time period covered by this report were directed to data collection and preprocessing, software development, measurements of surface wave characteristics, and constructing "master curves" for clusters of events in specific regions.
In the next year, we will greatly increase the volume of processed data and construct group velocity maps for Central and Southern Asia. The expected weak surface wave signals recorded by a network and improvement of the regional model of the lithosphere. This will provide means to enhance detection and location capabilities.

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DEVELOPMENT OF DISCRIMINATION, DETECTION, AND LOCATION CAPABILITIES IN CENTRAL AND SOUTHERN ASIA USING MIDDLE-PERIOD SURFACE WAVES RECORDED BY A REGIONAL ARRAY

1. Introduction

This research is dedicated to investigation of the relevance and use of intermediate period (5 - 25 s) surface wave data in problems of detection, discrimination, and the accurate location of small events using regional array data within a nonproliferation monitoring environment. It is focused on analysis of data from events (earthquakes throughout Central and Southern Asia and the Middle East and nuclear explosions at Lop Nor) within $15 - 25^o$ of the Kyrghiz Seismic Telemetry Network. The main goals are to:

• improve *detection capabilities* by developing techniques for extracting weak surface wave signals immersed in strong background noise using standard group and phase velocity curves and phase-stacking procedures;

• enhance *location capabilities* by improving existing 3D models of the regional crustal and uppermost mantle velocity structure and, in this way, providing a firm foundation for the application of a 3D location algorithm.

Our research work during the 6.5-month time period covered by this report has naturally divided into several steps:

• Data collection and preprocessing;

• Software development;

• Measurements of surface wave characteristics.

• Characterization of surface wave propagation across various tectonic regimes of Central and Southern Asia.

In following, we will describe the status of these efforts and the current results in each of the mentioned direction.

2. Data Collection and Preprocessing.

Earthquake and nuclear explosion data recorded by the Kyrghiz Telemetered Seismic Network (KNET) (Vernon, 1994) (Figure 1 and Table 1) between 1991 and 1995 have been used to study the characteristics of surface wave propagation across Central and Southern Asia. More than 200 events with body wave magnitude $M_b > 3.5$ and source depth less than 100 km within $15 - 25^o$ of KNET were selected for the analysis. In the first stage of analysis, 80 events with $M_b > 4.0$ were analyzed. Positions of epicenters for these events are shown on Figure 2. Many events are grouped in clusters inside small areas, providing the opportunity for path averaging to improve the statistics of the group velocity measurements. Source-network paths for the analyzed events are shown on

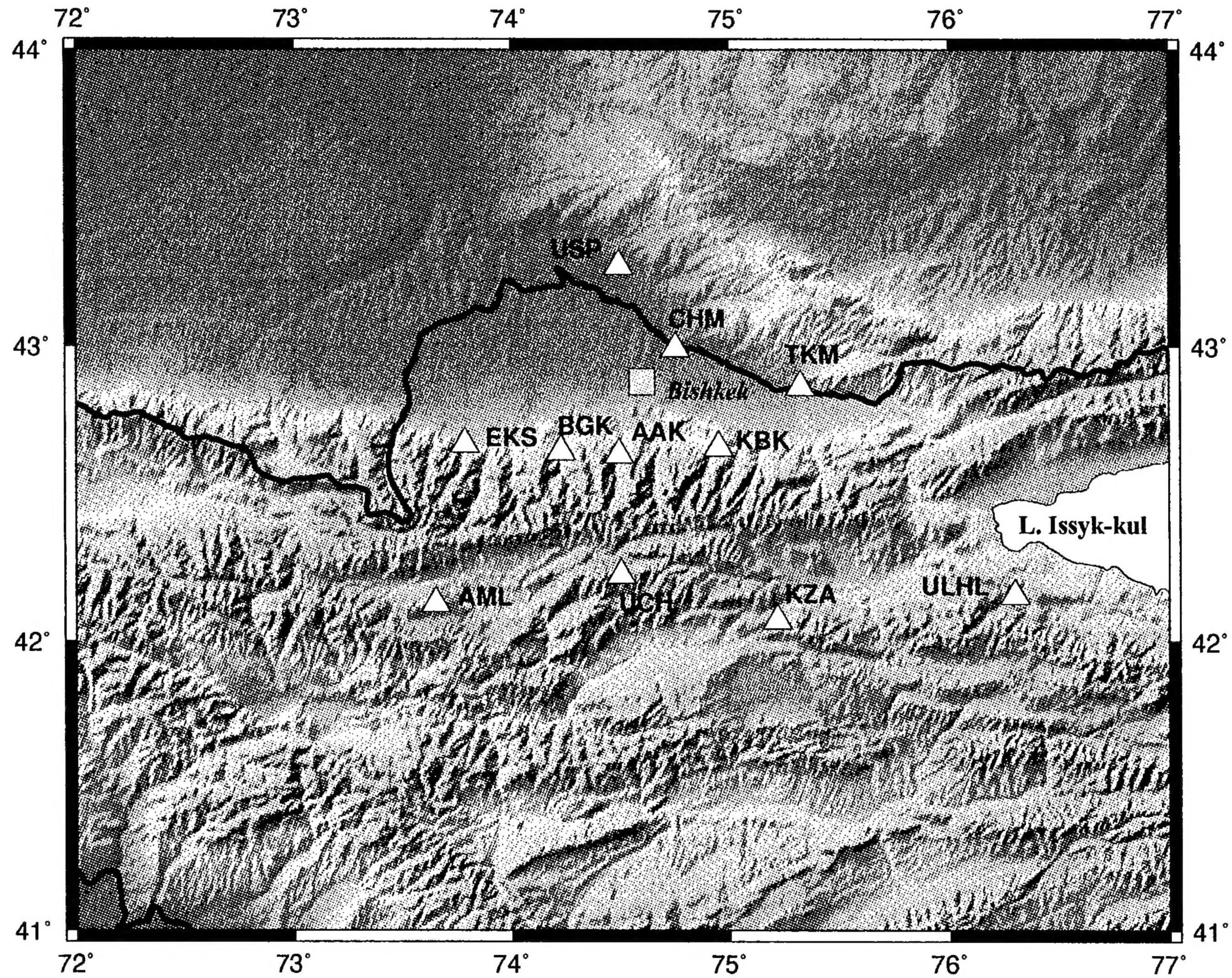

Figure 1. Kyrghyz Network

Table 1. Kyrghyz Seismic Network

Station	Latitude o, N	Longitude o, E	Elevation km	Operation Time from	till
CHM	42.9986	74.7513	0.6550	1/9/1991	now
EKS2	42.6615	73.7772	1.3600	1/9/1991	now
USP	43.2669	74.4997	0.7400	1/9/1991	now
BGK2	42.6451	74.2274	1.6400	1/9/1991	10/9/1993
AML	42.1311	73.6941	3.4000	1/9/1991	now
KZA	42.0778	75.2496	3.5200	1/9/1991	now
TKM	42.8601	75.3184	0.9600	1/9/1991	8/29/1994
KBK	42.6564	74.9478	1.7600	1/9/1991	now
AAK	42.6333	74.4944	1.6800	1/9/1991	now
UCH	42.2275	74.5134	3.8500	1/9/1991	now
ULHL	42.2456	76.2417	2.0400	5/9/1994	now
TKM2	42.9208	75.5966	2.0200	9/14/1994	now

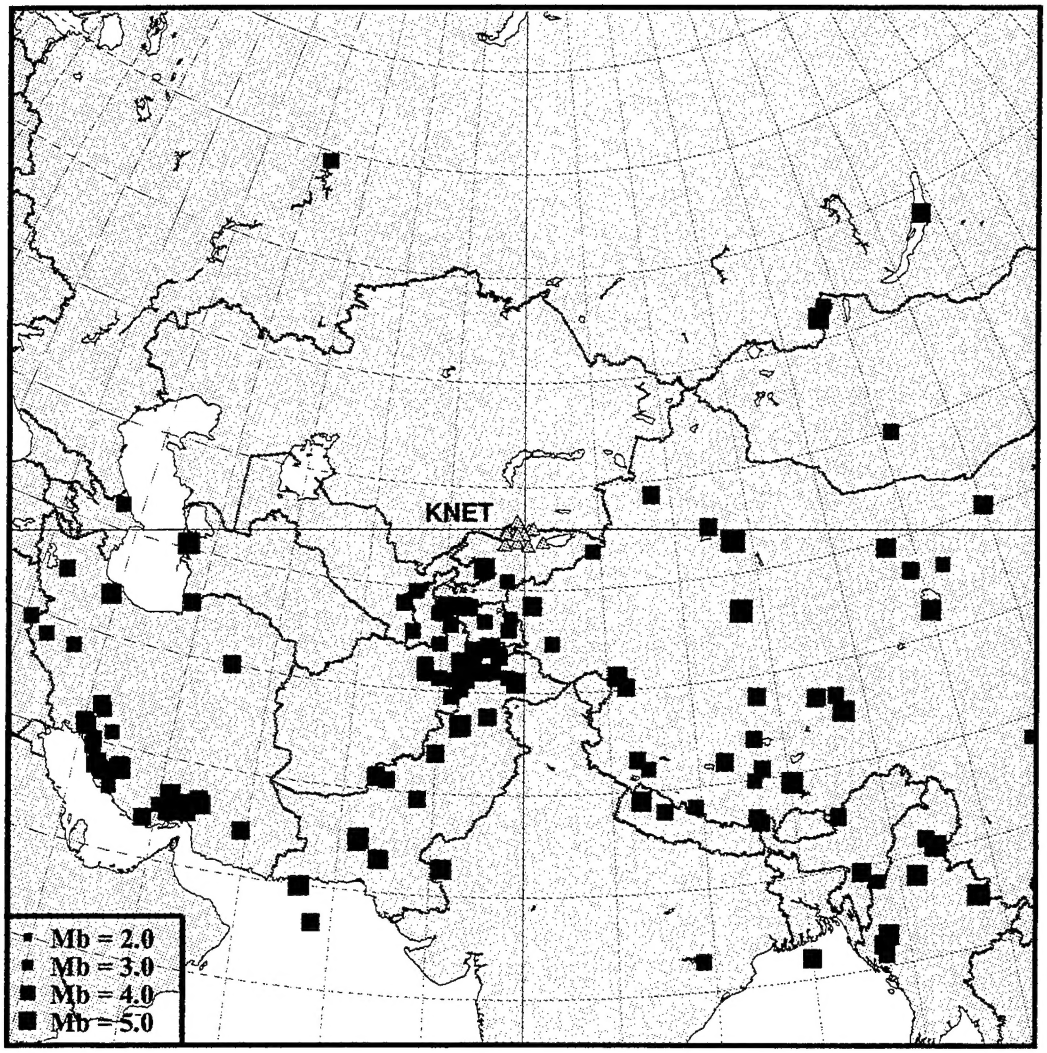

Figure 2. Source distribution for events for which several KNET stations are operating. Source symbol sizes are scaled linearly by body wave magnitude.

Figure 3.

Three-component records of all KNET stations operating at the time of a given event have been extracted from KNET's continuous broadband channels and have been completely preprocessed into event volumes. The sampling rate of these channels is 20 Hz, the number of operating stations varies with time from 4 to 10. The quality of records is normally quite good, the number of glitches and telemetric drops per a fixed time interval steadily decreases with operational time.

3. Software development.

The basic numerical elements for obtaining surface wave measurements had been developed by us prior the contract period (Levshin *et al.*, 1992, 1994). The recent innovation is that code has been developed which allows measurements to be made rapidly on relatively large volumes of data. This has required the development of rational parametric and waveform database structures and the development of relatively rapid graphical routines for human interaction with the data. The technique used will be briefly described below.

We continue to develop software for tomographic imaging and inversion of surface wave data. In addition, we will begin to develop software for stacking surface wave signals across the network during the next contract year.

4. Measurements of Surface Wave Characteristics.

Problems associated with the estimation of accurate surface wave characteristics (wave velocities, amplitudes, polarizations) do not change in nature with the spatial scale or frequency band of interest, although they do change in magnitude. The most significant issues concern the accrual of high quality data, the identification and extraction of unwanted signals, and the measurement of the signals of interest.

Data quality is quite good, as exemplified by the record section shown in Figure 4a. The main problem to be faced is that the structure under study is quite complicated. This not only makes interpretation in terms of structural models difficult, but also greatly complicates measurements; or more accurately complicates the identification of the aspects of the waveforms on which measurements are to be applied. Our aim, then, is to extract the signals we desire, related to nearly directly arriving waves that can be interpreted deterministically, from the potentially interfering multipaths and coda that are essentially stochastic in nature.

The basic characteristics of the current measurement procedure is based on a long history of development of surface wave analysis (e.g., Dziewonski *et al.*, 1969, 1972; Levshin *et al.*, 1972, 1989, 1992, 1994; Cara, 1973; Russell *et al.*, 1988). As described above, the recent innovation is that code has been developed which allows measurements to be made rapidly on relatively large

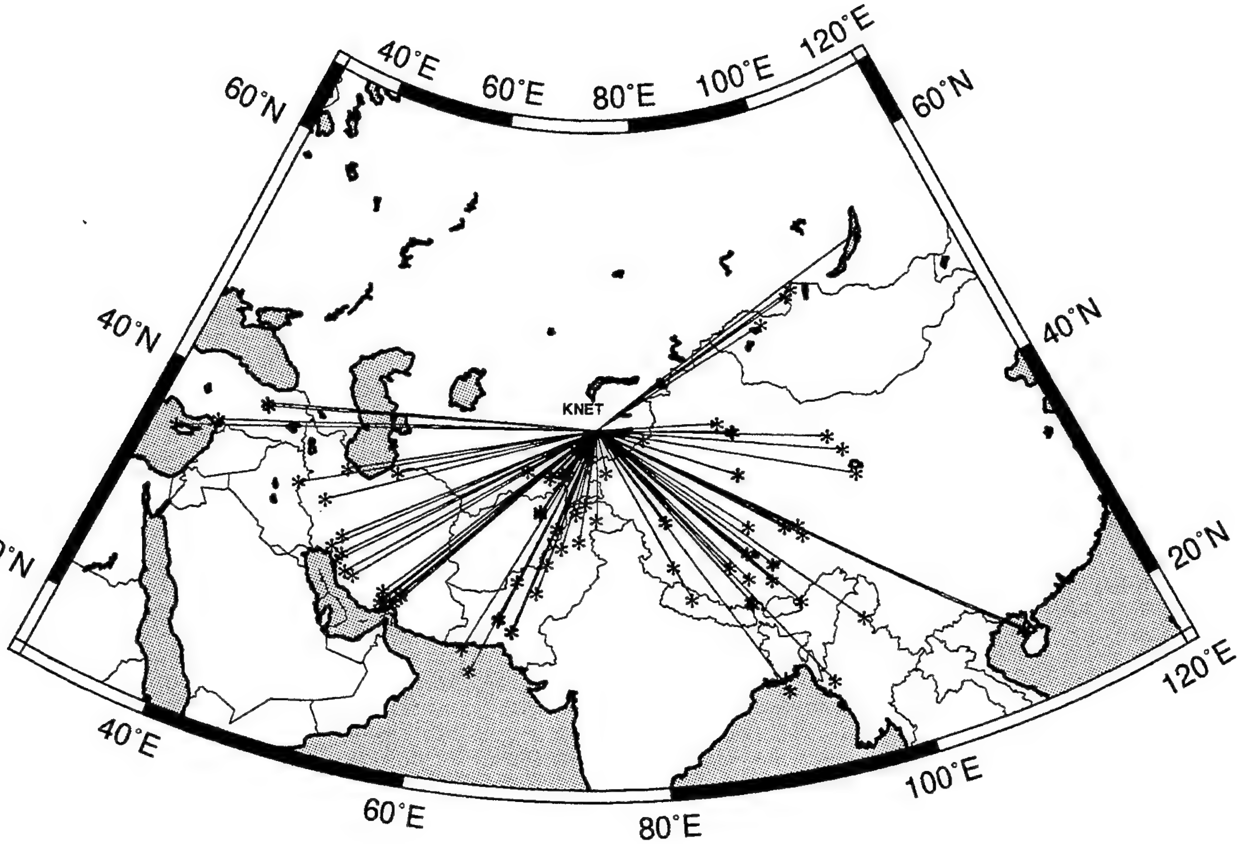

Figure 3. Source-station paths for selected events.

(a) ***Record Section of Z-components for KNET stations***

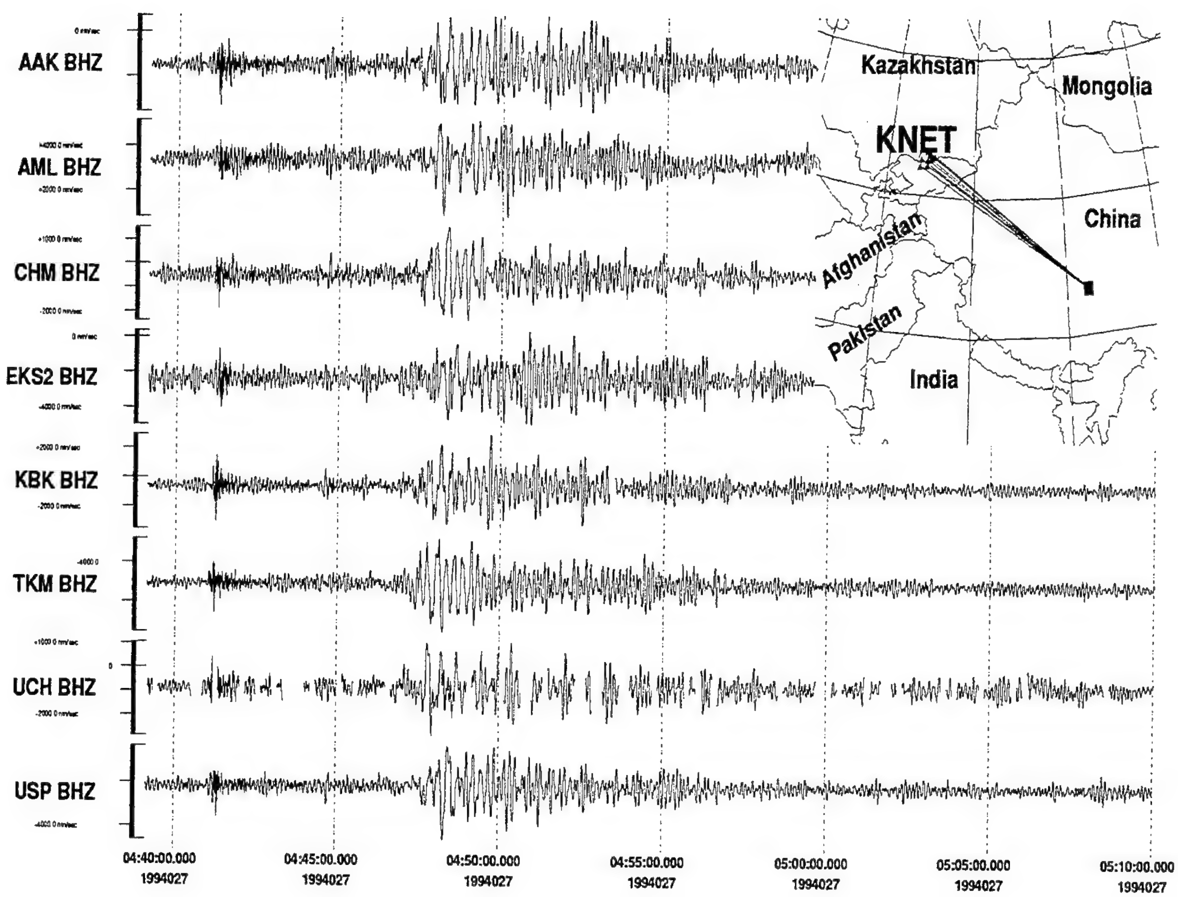

Figure 4. An example of surface wave data processing: Qinghai event on 1/27/1994, Ms=4.8

(a) Record section for vertical components. A path scheme is inserted.
(b) Group velocity - Period diagrams for the station USP.
(c) Group velocity measurements.
(d) Raw and filtered waveforms.

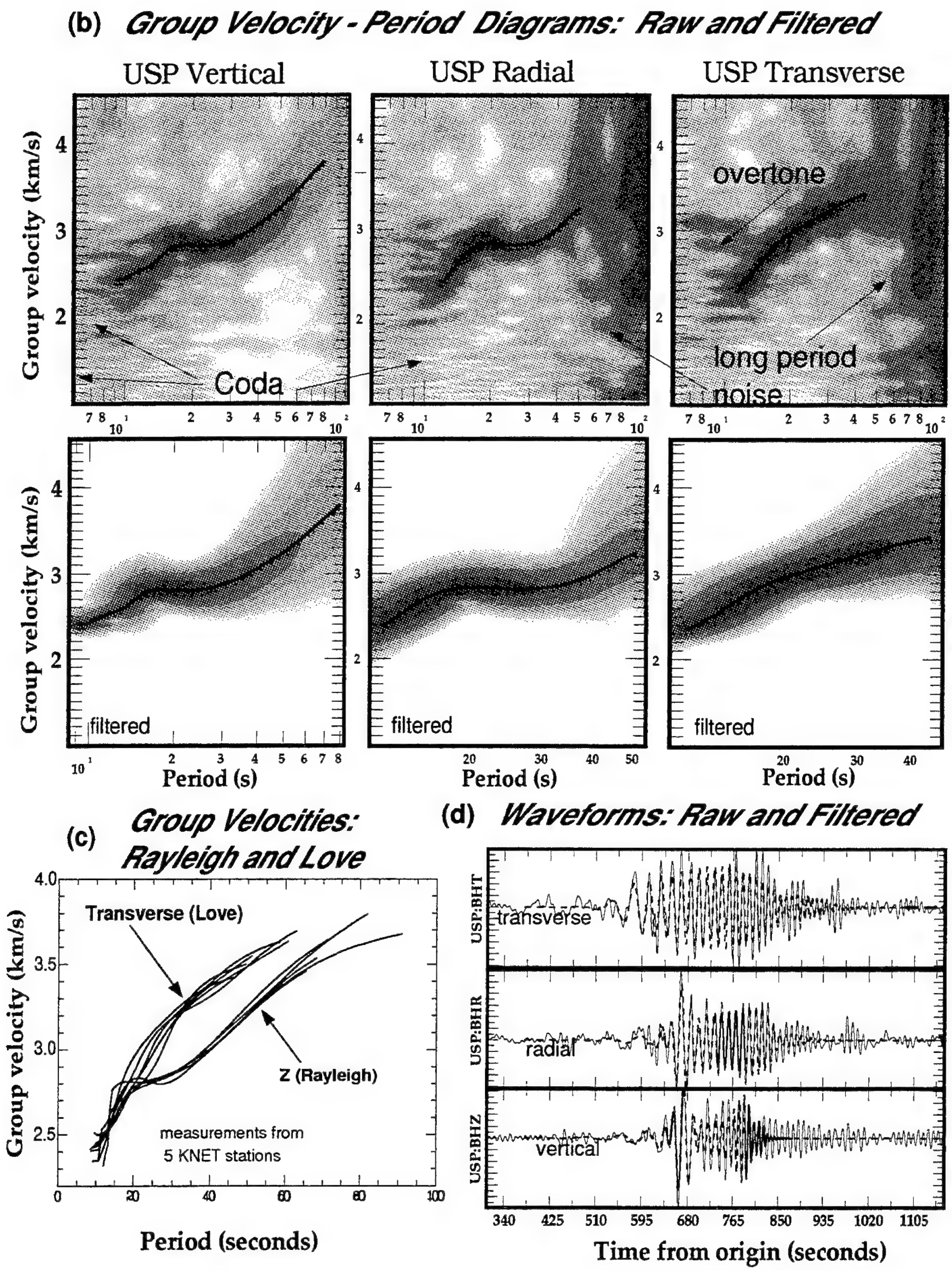

Figure 4. Continuation

volumes of data from heterogeneous networks and a variety of source regions whic can be stored into appropriate data base.

The general form of the measurement procedure is as follows. Group velocity - period diagrams for the vertical, radial, and transverse components are constructed. An analyst manually traces the apparent group velocity curve for the Rayleigh wave (on the vertical and radial components) and the Love wave (on the transverse component). Time-variable filters are applied around the selected curve to separate the desired signal from the 'noise'. This results in filtered group velocity - period diagrams for which contamination from interfering signals should be reduced. Group velocity, phase velocity, amplitude, and polarization measurements are automatically obtained on the filtered images.

To date, the method has been applied to waveform data from 80 events surrounding KNET (Table 2). Approximately 600 Love and Rayleigh wave dispersion curves have been obtained. Records for an additional 120 events which occurred in 1995 will be processed in the immediate future.

Figures 4a-d present an example the analysis of these data , in which unwanted signals, in particular surface wave coda, overtones, and body waves are greatly reduced in the filtered seismogram on which measurements are obtained. Seven KNET stations were operating during the passage of surface waves from an event in the Qinghai Province, China on 1/17/94 ($\Delta \approx 16$ degrees, $M_s = 4.8$). Rayleigh and Love wave group velocity measurements are shown in Figure 4bc. Rayleigh wave measurements are quite similar across the array above about 20 seconds period and for Love waves above about 30 seconds period at this azimuth. Variations across the array at shorter periods result both from real differences along the various wave paths near the network and also from Rayleigh - Love interference, which can be significant since the group velocities of the two wave types are similar in this period range. Cleaned and raw waveforms are presented in Figure 4d.

An unfortunate, but currently still necessary, characteristic of this procedure, is that it depends crucially on direct human interaction with potentially large volumes of seismic waveform data. The success of this method is based on the analyst accurately identifying the main dispersion ridge of the fundamental modes, separating the 'direct arrival' from surface wave coda at periods below about 10 seconds, inspecting interpolation near spectral holes, and truncating the measurements appropriately at long periods as the signals weaken. This interaction limits the speed with which the method can be applied, and, therefore, the volume of data that can be processed. The extreme complexity and variability of the wave patterns seen on many records and frequency-time diagrams due to lateral refraction, multipathing, and scattering makes the complete automation of surface wave measurements for periods less than 10-15 s in this region quite problematic.

Data Base Structure

All waveform and parametric data, as well as surface wave measurements, are stored in the CSS v. 3.0 relational database (Anderson *et al.*, 1990) plus extensions. This data base will be delivered

Table 2. EVENT LOCATIONS

N	DATE	DAY	TIME	LATITUDE	LONGITUDE	DEPTH	M_b	M_s
	m/d/y		hh:mm:ss	φ^0, N	λ^0, E	km		
1	9/15/1991	258	0:20:50	30.61	66.73	33.0	4.80	4.20
2	9/20/1991	263	11:16:11	36.19	100.0	13.0	5.50	5.00
3	11/08/1991	312	15:13:44	26.32	70.60	22.0	5.60	5.00
4	11/13/1991	317	21:04:29	30.75	50.08	33.0	5.10	4.50
5	11/15/1991	319	19:53:43	29.69	69.13	19.0	4.60	4.30
6	11/28/1991	332	17:19:55	36.92	49.60	16.0	5.60	5.00
7	12/14/1991	348	5:53:05	35.04	57.59	33.0	4.90	4.40
8	12/14/1991	348	8:20:23	33.97	88.84	33.0	5.10	4.60
9	12/19/1991	353	18:55:17	28.10	57.30	27.0	5.30	4.80
10	12/21/1991	355	19:52:45	27.90	88.13	57.0	4.90	4.20
11	12/28/1991	362	9:07:03	51.09	98.06	17.0	5.00	4.70
12	1/04/1992	004	3:35:21	31.95	69.99	29.0	5.00	5.10
13	1/20/1992	020	8:58:22	27.39	65.99	27.0	5.20	5.20
14	1/21/1992	021	22:07:58	26.63	67.19	26.0	5.40	5.20
15	1/22/1992	022	10:48:39	26.57	67.31	33.0	4.30	4.30
16	1/24/1992	024	5:04:47	35.51	74.52	47.0	5.40	4.20
17	1/30/1992	030	5:22:01	24.95	63.14	29.0	5.50	5.60
18	2/14/1992	045	8:18:25	53.89	108.8	21.0	5.30	5.30
19	3/03/1992	063	18:35:02	28.35	57.14	33.0	4.80	4.10
20	3/04/1992	064	11:57:53	31.72	50.77	18.0	4.90	4.60
21	3/09/1992	069	16:59:28	27.42	66.04	19.0	4.90	4.10
22	3/13/1992	073	17:18:39	39.71	39.60	27.0	6.20	6.80
23	3/15/1992	075	16:16:24	39.53	39.92	21.0	5.50	5.80
24	3/24/1992	084	19:32:10	31.54	81.54	16.0	4.80	4.40
25	3/24/1992	084	21:01:47	33.83	72.90	14.0	5.00	4.20
26	3/27/1992	087	10:39:30	35.99	72.54	35.0	4.90	4.50
27	3/28/1992	088	10:17:41	26.58	67.30	10.0	4.90	4.30
28	4/04/1992	095	17:43:20	28.14	87.97	33.0	4.90	4.60
29	4/13/1992	104	3:47:51	31.95	88.33	33.0	4.60	4.50
30	4/24/1992	115	7:07:23	27.55	66.06	25.0	5.90	6.10
31	5/05/1992	126	13:57:51	29.74	50.83	40.0	4.60	4.50
32	5/05/1992	126	15:57:40	30.04	50.81	10.0	4.40	4.20
33	5/11/1992	132	11:23:41	36.79	73.48	33.0	4.70	4.10
34	5/15/1992	136	5:57:00	36.00	73.19	33.0	4.20	4.30
35	5/19/1992	140	12:24:57	28.29	55.59	33.0	5.70	5.00
36	5/20/1992	141	12:20:32	33.37	71.31	16.0	6.00	6.00
37	5/21/1992	142	4:59:57	41.60	88.81	0.0	6.50	5.00
38	6/05/1992	157	0:23:43	33.24	71.22	33.0	4.90	4.50
39	6/13/1992	165	15:40:05	28.94	82.92	33.0	4.60	4.90
40	6/21/1992	173	11:19:39	38.30	99.42	20.0	4.80	5.00

N	DATE	DAY	TIME	LATITUDE	LONGITUDE	DEPTH	M_b	M_s
	m/d/y		hh:mm:ss	φ^0, N	λ^0, E	km		
41	6/27/1992	179	2:13:18	35.14	81.07	33.0	4.50	4.60
42	6/27/1992	179	13:21:20	35.13	81.13	33.0	5.00	4.70
43	7/08/1992	190	10:09:48	21.05	93.68	43.0	5.40	4.80
44	7/09/1992	191	21:34:02	21.00	89.97	29.0	5.30	4.60
45	7/19/1992	201	3:58:00	23.25	63.97	17.0	4.80	4.20
46	7/30/1992	212	8:24:46	29.58	90.16	14.0	5.90	5.80
47	10/02/1993	275	1:17:30	39.06	69.96	14.0	5.00	4.40
48	10/02/1993	275	8:42:32	38.19	88.66	14.0	6.20	6.30
49	10/02/1993	275	9:43:19	38.16	88.60	14.0	5.80	5.30
50	10/02/1993	275	17:23:33	38.17	88.69	14.0	5.60	5.00
51	1/11/1994	011	0:51:56	25.23	97.20	10.0	6.00	5.90
52	1/27/1994	027	4:37:14	33.40	92.22	33.0	4.80	4.80
53	2/10/1994	041	2:24:35	39.12	71.58	24.0	4.70	4.10
54	2/10/1994	041	6:15:18	36.96	35.82	17.0	4.90	4.30
55	6/20/1994	171	9:09:02	28.96	52.61	9.0	5.90	5.70
56	6/29/1994	180	18:22:33	32.56	93.67	10.0	5.90	5.60
57	7/11/1994	192	20:57:37	37.54	54.47	29.0	4.80	4.30
58	7/23/1994	204	20:57:59	31.06	86.54	16.0	5.10	5.00
59	8/31/1994	243	4:19:13	49.48	94.21	33.0	5.00	4.10
60	1/03/1995	003	11:21:45	27.74	56.29	41.0	4.50	-
61	1/04/1995	004	2:22:12	27.54	56.53	33.0	4.60	-
62	1/10/1995	010	10:09:51	20.20	109.1	33.0	5.20	5.50
63	1/17/1995	017	22:15:49	34.65	70.76	27.0	4.60	-
64	1/21/1995	021	3:02:32	29.01	52.05	33.0	4.70	-
65	1/24/1995	024	4:14:26	27.56	55.63	33.0	4.90	-
66	1/24/1995	024	4:52:05	27.38	55.52	0.0	4.31	-
67	2/02/1995	033	19:34:49	39.32	67.49	33.0	4.60	-
68	2/10/1995	041	7:49:19	36.18	69.11	44.0	4.60	-
69	2/10/1995	041	8:17:48	36.08	69.12	33.0	4.60	-
70	2/23/1995	054	21:03:01	35.04	32.27	10.0	5.80	5.70
71	2/11/1995	042	6:01:11	36.16	69.07	33.0	4.10	-
72	2/12/1995	043	10:56:58	33.28	93.38	27.0	4.80	4.60
73	2/17/1995	048	2:44:25	27.63	92.37	39.0	5.20	5.10
74	2/20/1995	051	4:12:23	39.16	71.11	26.0	5.40	-
75	2/20/1995	051	8:07:34	41.07	72.45	39.0	5.00	4.50
76	2/24/1995	055	15:27:18	51.21	98.15	30.0	4.50	-
77	3/03/1995	062	13:51:22	34.59	45.20	33.0	4.50	-
78	3/16/1995	075	3:27:02	30.12	67.56	29.0	4.80	4.20
79	3/22/1995	081	6:28:36	30.20	51.04	33.0	4.80	
80	3/25/1995	084	11:23:27	33.83	47.90	33.0	4.60	

to the funding agents upon completion of the contracts. The standard relations (affiliation, event, gregion, instrument, network, origin, sensor, site, sitechan, sregion, wfdisc) are augmented with two event relations modified slightly from CSS v. 2.8 (centryd, moment) and three extensions (disp, ftdisc, wfedit). The wfedit relation contains information about the time, duration and nature of waveform problems (e.g., clips, gaps, nonlinearities, interfering events, etc.). The disp and ftdisc relations point to dispersion measurements and group velocity - period images, respectively. For each station:event pair, raw and filtered group velocity images are output and pointed to by the ftdisc relation. Dispersion measurements (group velocity, phase velocity, spectral amplitude, polarization) are output and pointed to by the disp relation. Cleaned or filtered waveforms are output and pointed to by a cleaned wfdisc relation.

5. Surface Wave Group Velocities across Central and Southern Asia.

The selected events are naturally segregated in several clusters. The most well represented clusters are situated in South-Western Turkmenia, Northern Turkey and Cyprus, Northern, Western and Southern Iran, Southern Pakistan, Tibet, Lop Nor, Mongolia. On the way to KNET, surface waves from these clusters cross such dramatically different tectonic regimes as the Tien Shan, Pamir, Hindu Kush, Karakoram, Kunlun, Elburz, Kopet, Zagros, and Himalayan Mountains; the Tibetan and Iranian plateaus; the Tarim Basin,the Turkmenian Platform; and the Indian Shield. The differences in surface topography along these paths are among the greatest in the world (more than 6 km for some paths) and variations in sedimentary thickness are even greater, with thicknesses ranging from more than 15 km in the eastern part of Tarim basin near Lop Nor to essentially zero in Mongolia. Crustal thicknesses in the region, according to Molnar(1988), vary from 40 to 70 km.

Group velocity measurements have been performed for more than 80 events belonging to the forementioned clusters. Approximately 350 Rayleigh wave dispersion curves and 250 Love wave dispersion curves for waves excited at these sites and recorded by KNET stations have been obtained. Results from some group velocity measurements are shown in Figure 5. The great variability of group velocities clearly illustrates complicated structures in this region and strong variations in surface wave propagation across different tectonic regimes. The variability of amplitude and polarization parameters of Love waves across the network for the event in Pakistan is demonstrated by Figure 6. Such variability implies that to make stacking procedures efficient it is necessary to introduce azimuthal and range dependent corrections for individual stations of the network.

6. Conclusions and Future Plans

Current results of our study can be summarized as follows:

- An innovative technique for surface wave analysis was developed which allows phase and group velocity, amplitude and polarization measurements to be made rapidly on relatively large volumes

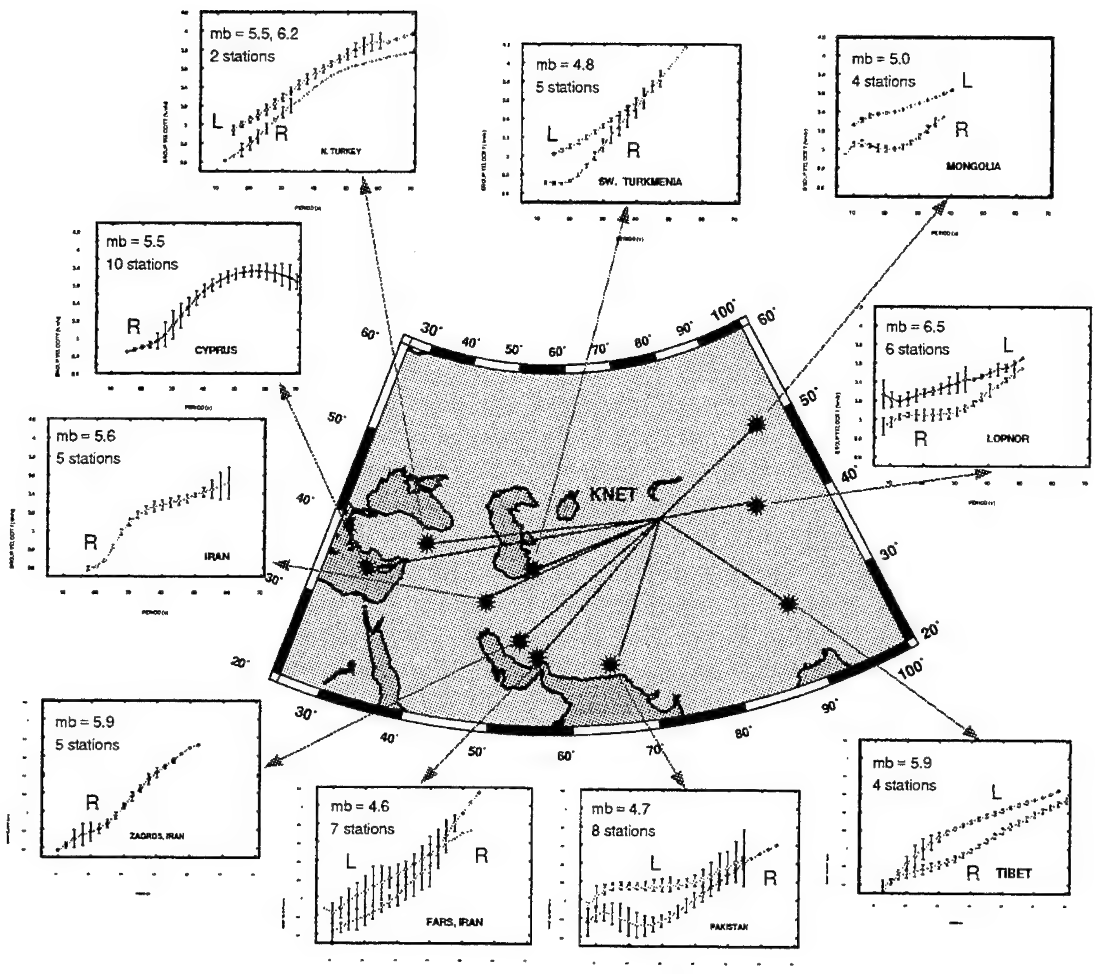

Figure 5. Group velocity variability across KNET is presented for Rayleigh (R) and Love (L) waves. One standard deviation 'error bars' are shown at periods where measurements from at least 3 stations exist, in order to represent the variability observed for a variety of source regions around Central and Southern Asia.

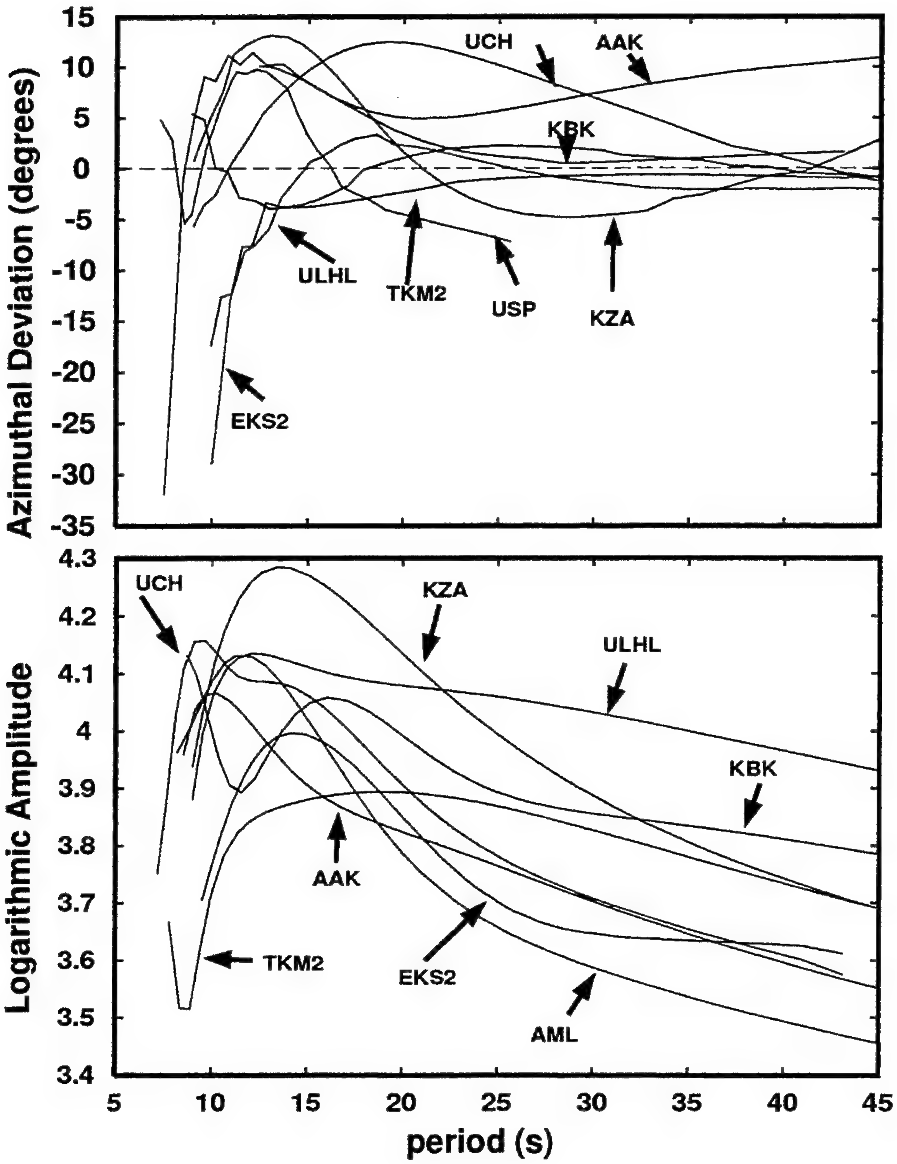

Figure 6. Polarization and amplitude measurements for a magnitude mb = 4.7 event in Pakistan, recorded at 8 KNET stations. Strong amplitude variability is typically observed across the network.

of data from heterogeneous networks and a variety of source regions.

• A data base of surface wave raw and filtered records with accompanying parametric information has been created by application of this technique to broadband records of Kyrghiz Telemetered Seismic Network between 1991 and 1995. This data base includes records and measurements for 80 events in different parts of Asia (from Turkey and Iran to the West from KNET, from Pakistan and India - to the South, from China and Mongolia to the East. Paths from these events cross drastically different tectonic regimes.

• Group velocity measurements for surface waves from clustered events have been used to construct standard Rayleigh and Love wave group velocity curves in the period range from 5-10 and 30-40 s for a number of paths between KNET and seismic areas in Turkey, Iran, Pakistan, China, Turkmenia, Mongolia, and the Chinese test site at Lop Nor.

Future developments will be along the following lines.

- We will further extend the surface wave data base. This will be done (a) by processing $\approx$ 120 additional events recorded by KNET in 1995; (b) by adding measurements performed on records from from GSN, CDSN, and GEOSCOPE networks deployed in the same region (AFOSR Grant No. 49620- 95-0139); (c) by adding measurements performed on records of PASSCAL stations during the Tibetan Plateau experiment and stations of the FSU (Wu & Levshin, 1994; Wu *et al.*, 1996). We expect, in this way, to obtain $\approx$ 1500 independent wave paths and to use velocity measurements along them in a tomographic inversion for crustal V_s structures.

- High-resolution phase and group velocity maps in Central Asia will be constructed using the described measurements. We expect the spatial resolution of these maps to be on the order of 250-400 km for the region to the West, South and East from KNET at ranges less than 25^o.

- These maps will be used to develop surface wave stacking/array processing methods for regional broadband arrays located in the geologically complex setting . Such methods must incorporate differences in the dispersion characteristics among stations in the stack.

7. Contributing Researchers.

Dr. L. Ratnikova, S. S. Smith, and C. S. Lee contributed to the research in this report.

8. Related Contracts and Publications.

No other contracts were used to support the results given in this report.

The following publications were produced with support from this contract.

Ritzwoller, M. H., A. L. Levshin, S. S. Smith, and C. S. Lee, 1995. Making accurate continental

broadband surface wave measurements. *Proceedings of the 17th Seismic Research Symposium on Monitoring and Comprehensive Ban Treaty, Phillips Laboratory, Scottsdale, AZ, Sept. 1995*, 482-491, PL-TR-95-2108. ADA310037

9. References

Anderson, J., W. E. Farrell, K. Garcia, J. Given, H. Swanger, 1990. Center for Seismic Studies Version 3 Database: Schema Reference Manual, *CSS Technical Report C90-01, September, 1990.*

Cara, M., 1973. Filtering of dispersed wave trains, *Geophys. J. R. astr. Soc.*, **33**, 65 - 80.

Dziewonski, A. M., S. Bloch, and M. Landisman, 1969. A technique for the analysis of transient seismic signals, *Bull. seism. Soc. Am.*, **59**, 427 - 444, 1969.

Dziewonski, A. M., J. Mills, and S. Bloch, 1972. Residual dispersion measurements: a new method of surface wave analysis, *Bull. seism. Soc. Am.*, **62**, 129 - 139.

Dziewonski, A. M., and D. L. Anderson, 1981. Preliminary Reference Earth Model, *Phys. Earth Planet. Int.*, **25**, 297-356.

Levshin, A. L., Pisarenko, V. F., and G. A. Pogrebinsky, 1972. On a frequency-time analysis of oscillations, *Ann. Geophys.*, **28**, 211 - 218.

Levshin, A. L., T. B. Yanovskaya, A. V. Lander, B. G. Bukchin, M. P. Barmin, L. I. Ratnikova, and E. N. Its, 1989. *Seismic surface waves in a laterally inhomogeneous Earth*, (ed. V. I. Keilis-Borok), Kluwer Publ., Dordrecht.

Levshin, A. L., L. I. Ratnikova, and J. Berger, 1992. Peculiarities of surface wave propagation across Central Eurasia, *Bull. seism. Soc. Am.*, **82**, 2464 - 2493.

Levshin, A. L., M. H. Ritzwoller, and L. I. Ratnikova, 1994. The nature and cause of polarization anomalies of surface waves crossing northern and central Eurasia. *Geophys. J. Int.*, 117, 577-590.

Levshin, A. L., and M. H. Ritzwoller, 1995. Characteristics of surface waves generated by events on and near the Chinese nuclear test site, *Geophys. J. Int.*, **123**, 131-148.

Levshin, A. L., M. H. Ritzwoller, and L. I. Ratnikova. Surface wave group velocity measurements across Eurasia, 1995. *Proceedings of the the 17th Seismic Research Symposium on Monitoring and Comprehensive Ban Treaty, Phillips Laboratory, Scottsdale, AZ, Sept. 1995*, 226-236, PL-TR-95-2108. ADA310037

Levshin, A. L., and M. H. Ritzwoller, 1995. High-resolution surface wave group velocity tomography of Eurasia. *EOS, Transactions*, **76**, No 46, 386.

Molnar, P., 1988. A review of geophysical constraints on the deep structure of the Tibetan Plateau, the Himalaya and the Karakoram, and their tectonic implications. *Phil. Trans. R. Soc. Lond.*, A, **326**, 33-88.

Ritzwoller, M. H., A. L. Levshin, S. S. Smith, and C. S. Lee, 1995. Making accurate continental broadband surface wave measurements. *Proceedings of the 17th Seismic Research Symposium on Monitoring and Comprehensive Ban Treaty*, Phillips Laboratory, Scottsdale, AZ, Sept. 1995, 482-491, PL-TR-95-2108. ADA310037

Russell, D. W., R. B. Herrman, and H. Hwang, 1988. Application of frequency-variable filters to surface wave amplitude analysis, *Bull. seism. Soc. Am.*, **78**, 339 - 354.

Vernon, F. , 1994. The Kyrghyz Seismic Network, *IRIS Newsletter*, **XIII**, 7-8.

Wu, F. T. and A. Levshin, 1994. Surface wave tomography of China using surface waves at CDSN. *Phys. Earth & Planet Inter.*, **84**, No. 1-4 , 59-77.

Wu, F. T., Levshin, A. L., and V. M. Kozhevnikov, 1996. Rayleigh wave group velocity tomography of Siberia, China and the Vicinity, (*in press*).

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